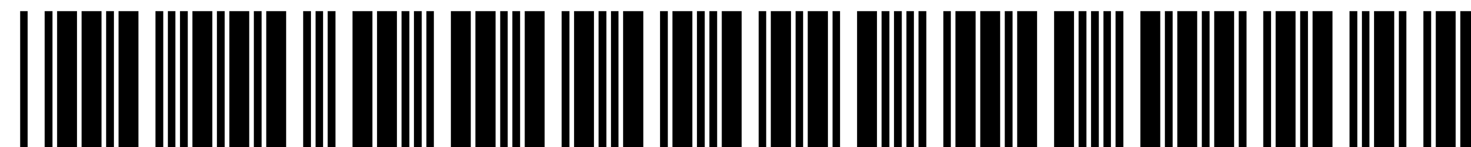

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Pieper et al.

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(54) **METHOD AND APPARATUS FOR AVOIDING DAMAGE WHEN ANALYSING A SAMPLE SURFACE WITH A SCANNING PROBE MICROSCOPE**

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(58) **Field of Classification Search**
CPC G01Q 10/065; G01Q 60/24
USPC 850/1, 3, 4, 33, 36–39, 44
See application file for complete search history.

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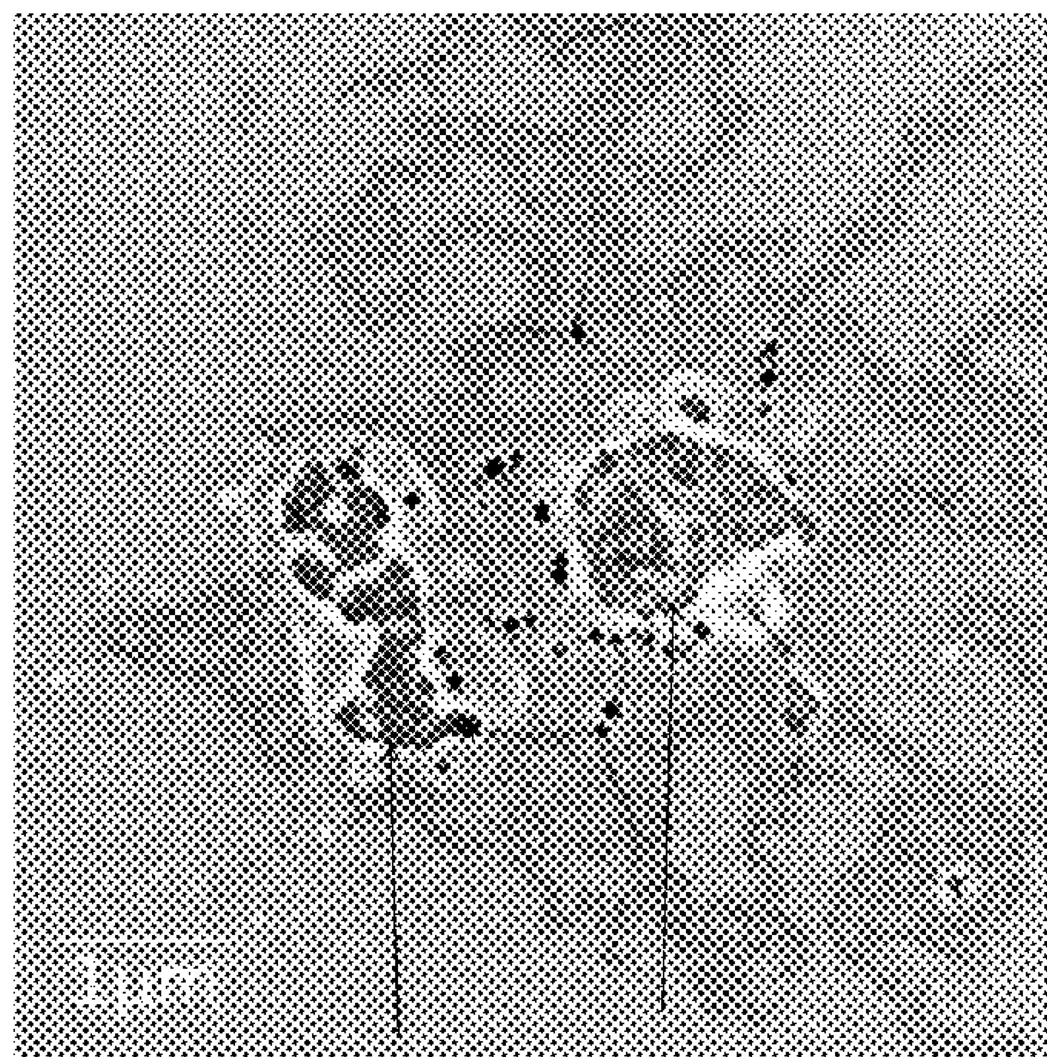
(57) **ABSTRACT**

The present application relates to a method for avoiding damage when analyzing a sample surface with a scanning probe microscope, the method comprising the step of: detecting an electrostatic interaction between a charging of the sample surface and a measuring tip of the scanning probe microscope in the course of the approach of the measuring tip to the sample surface already at a distance from the sample surface which is greater than the distance of the measuring tip when analyzing the sample surface.

24 Claims, 8 Drawing Sheets



ESD damage to a photomask

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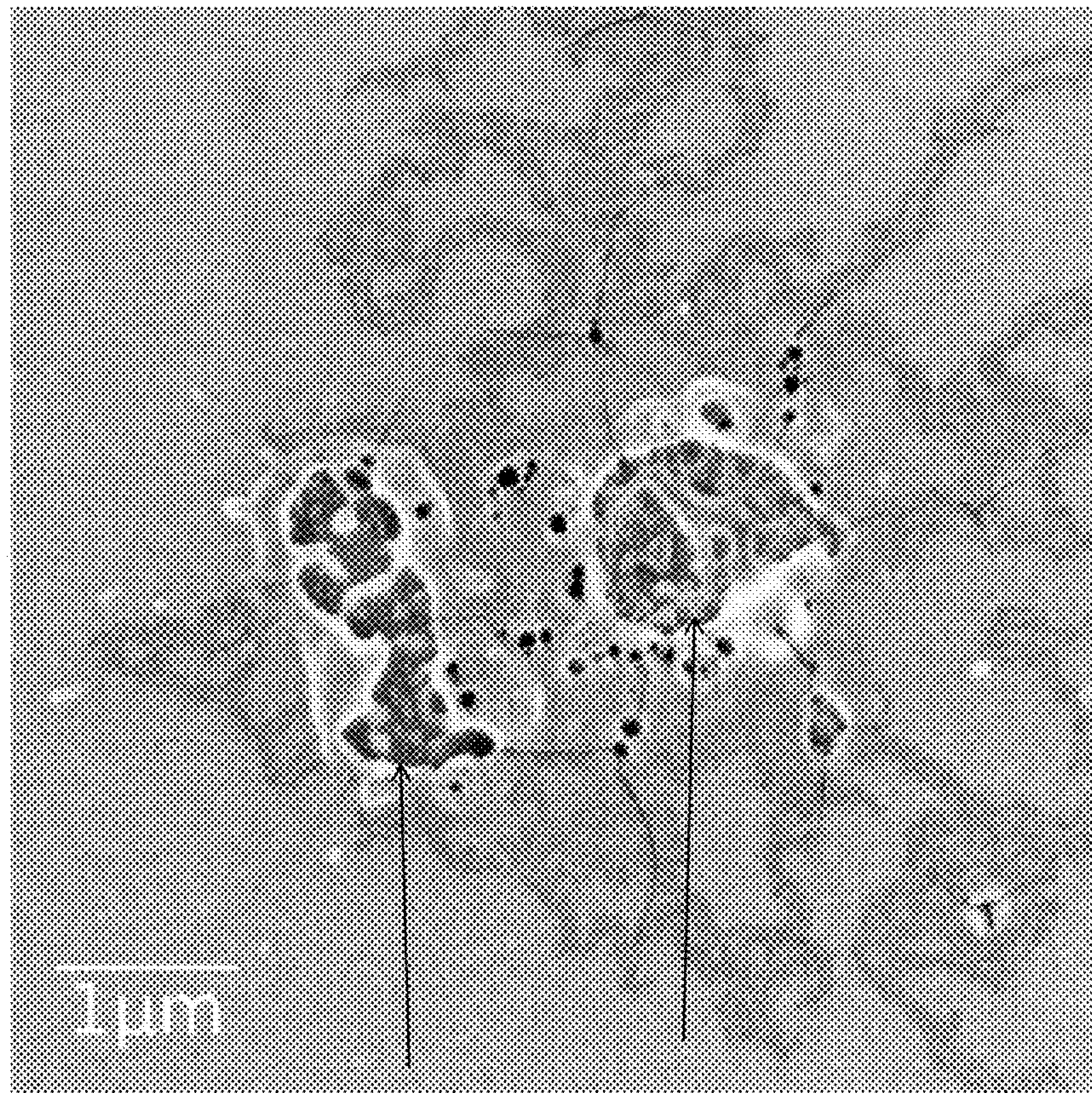


ESD damage to a photomask

FIG. 1

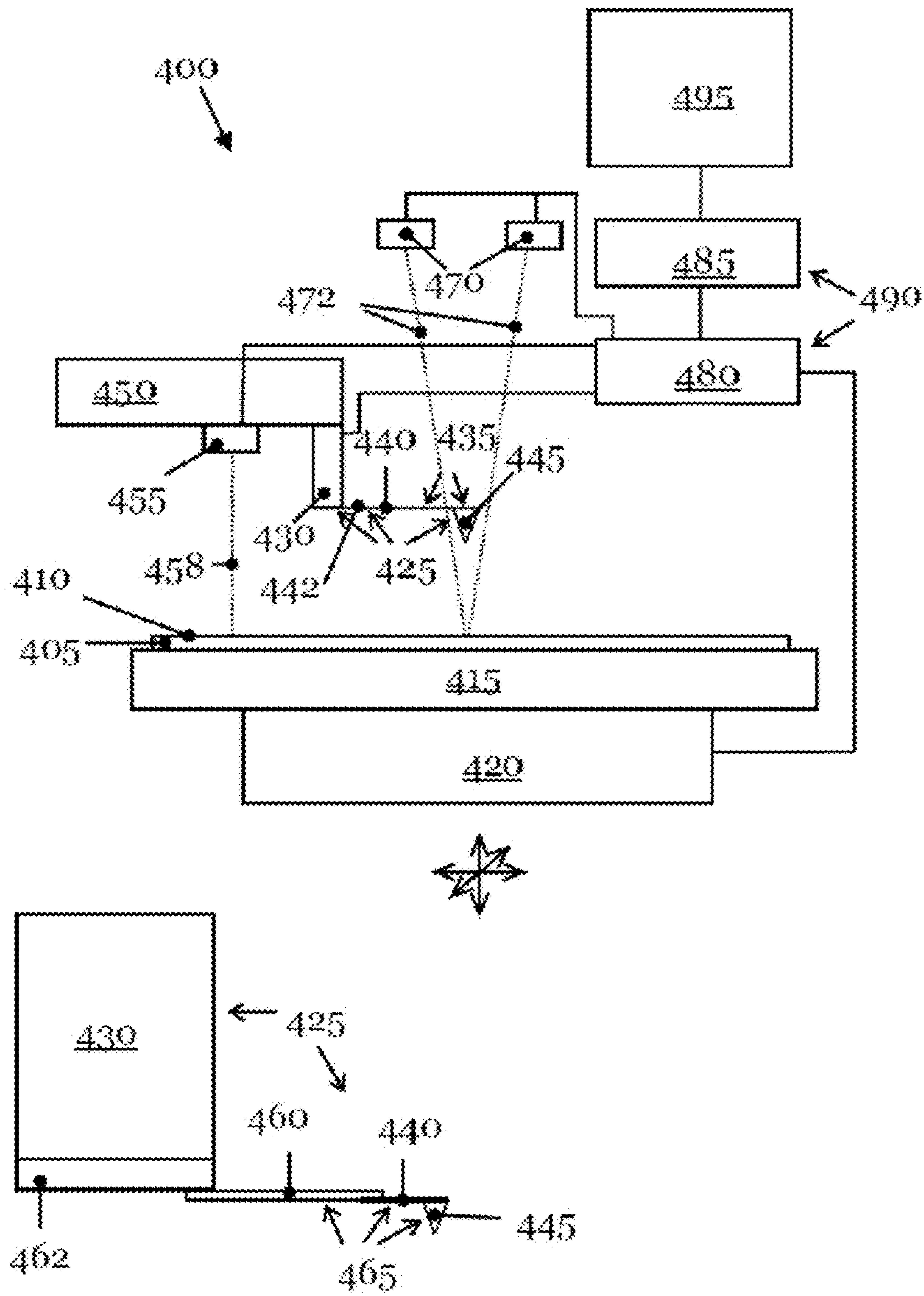


FIG. 2

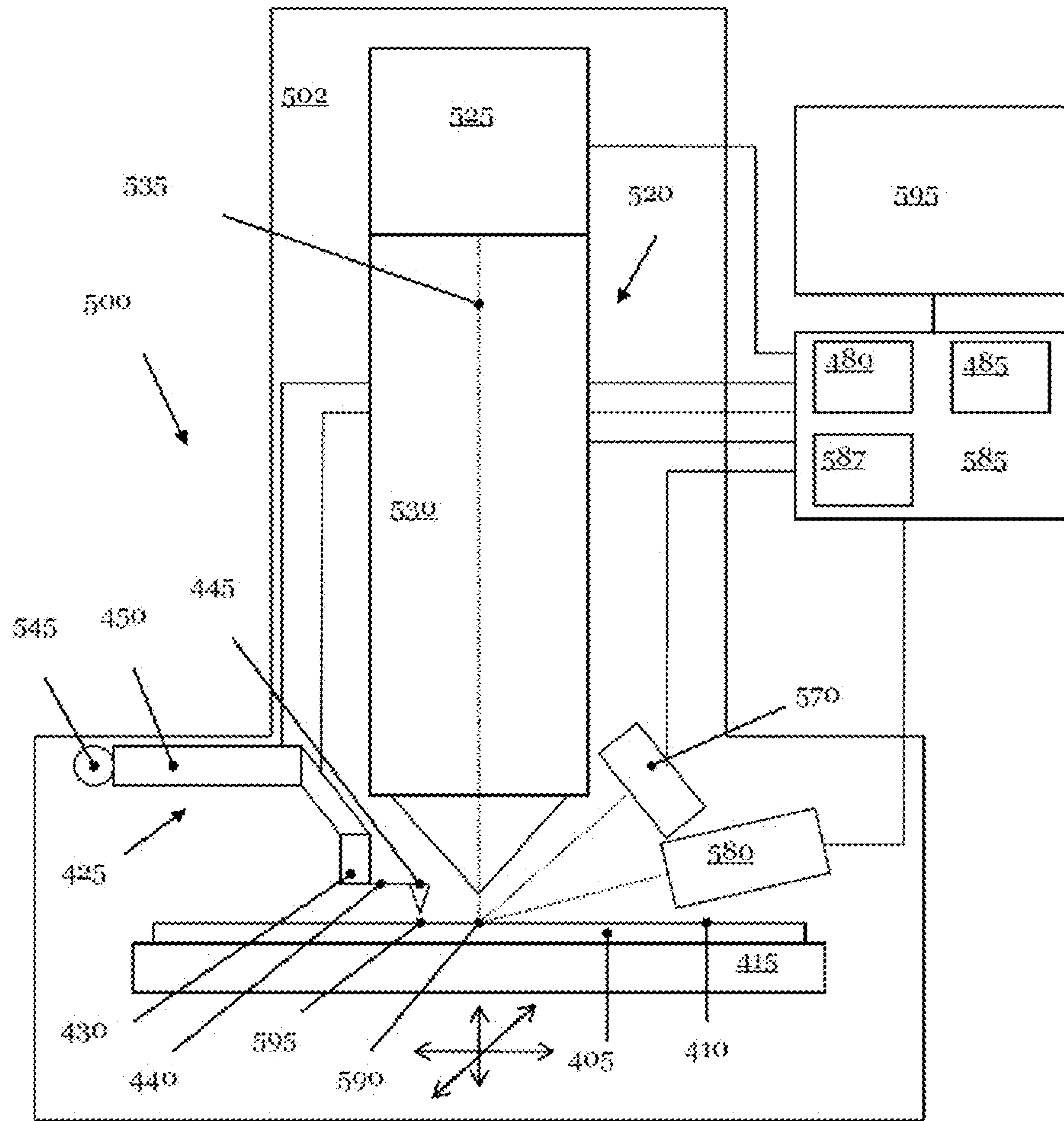


FIG. 3

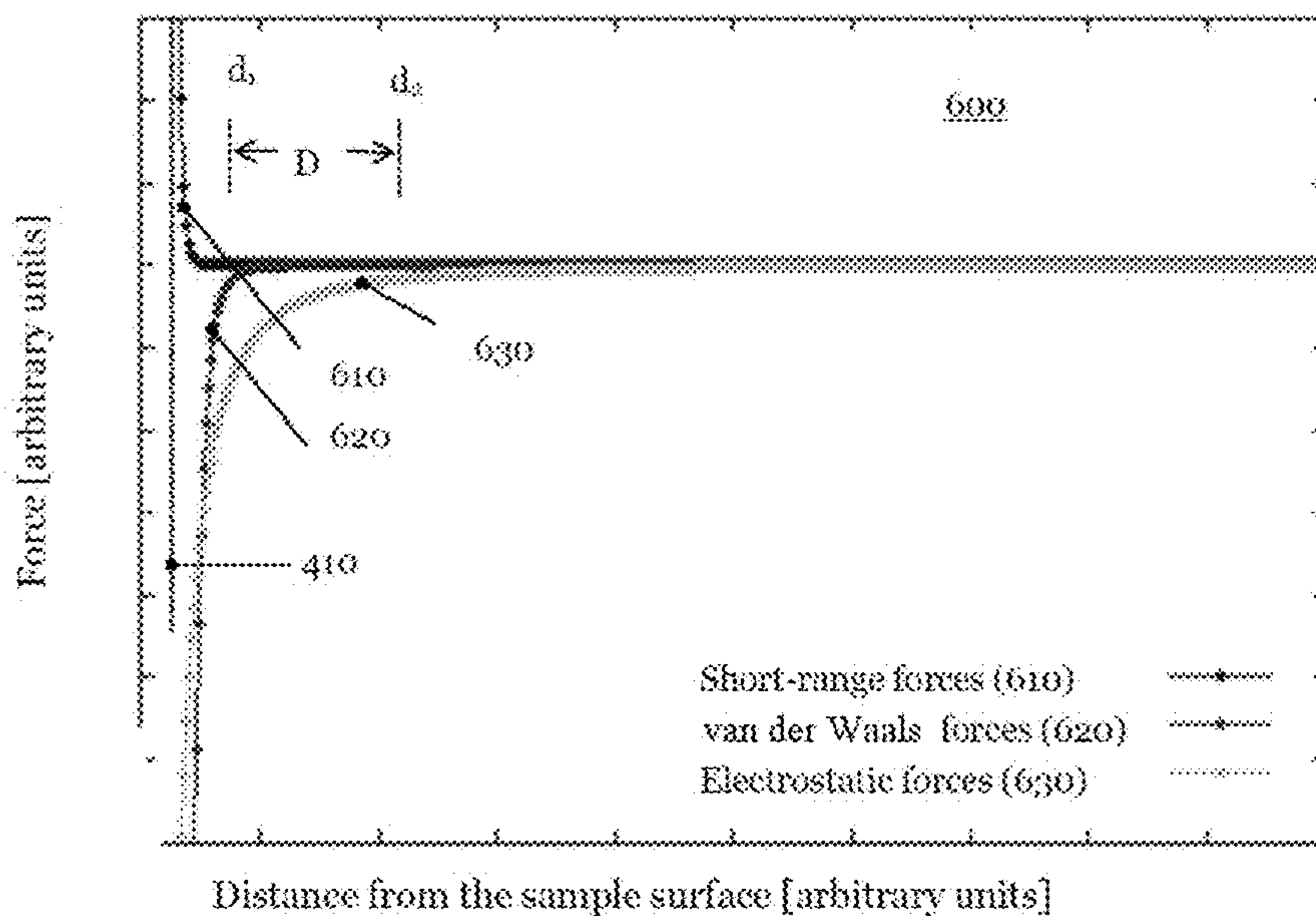


FIG. 4

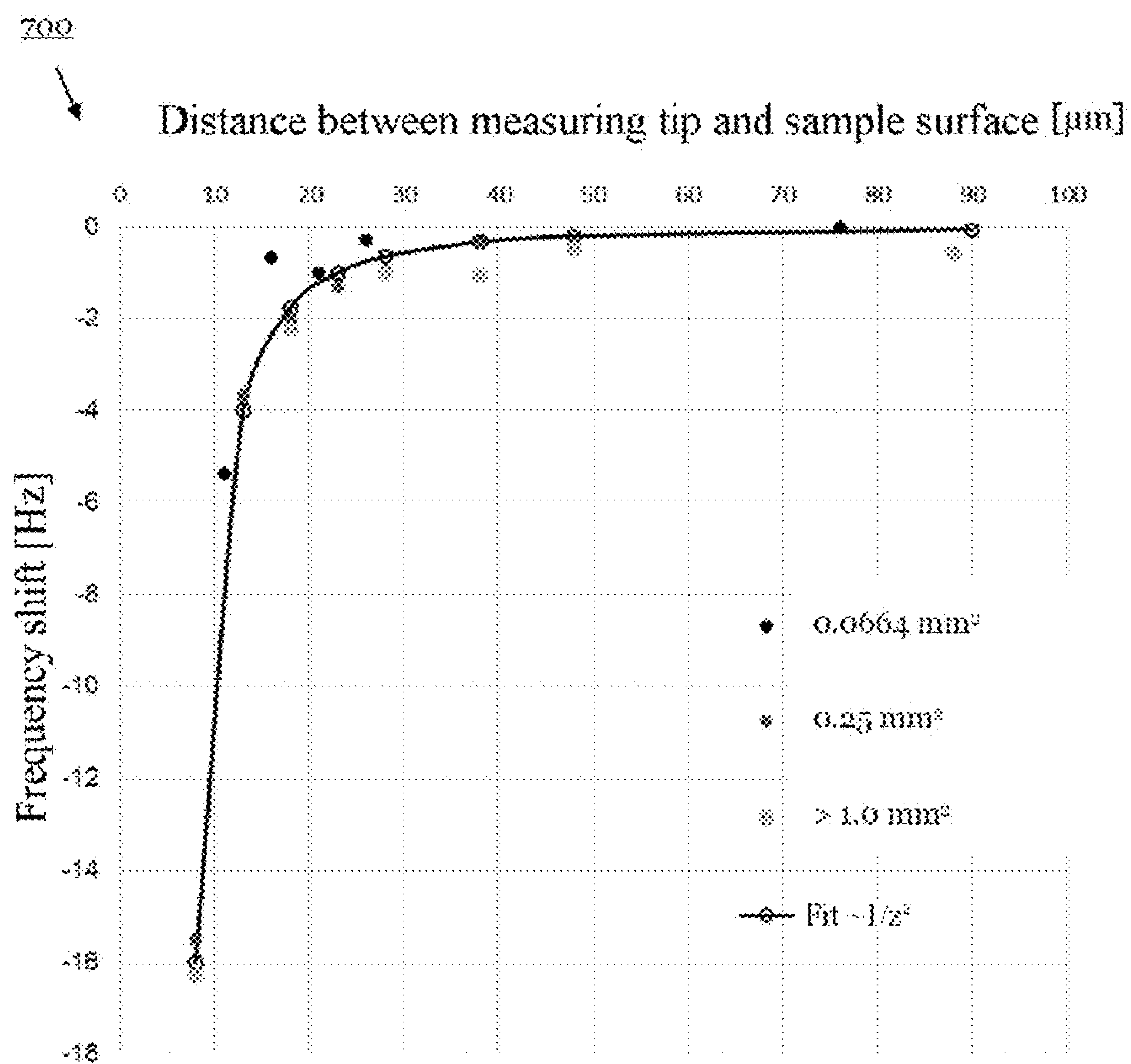


FIG. 5

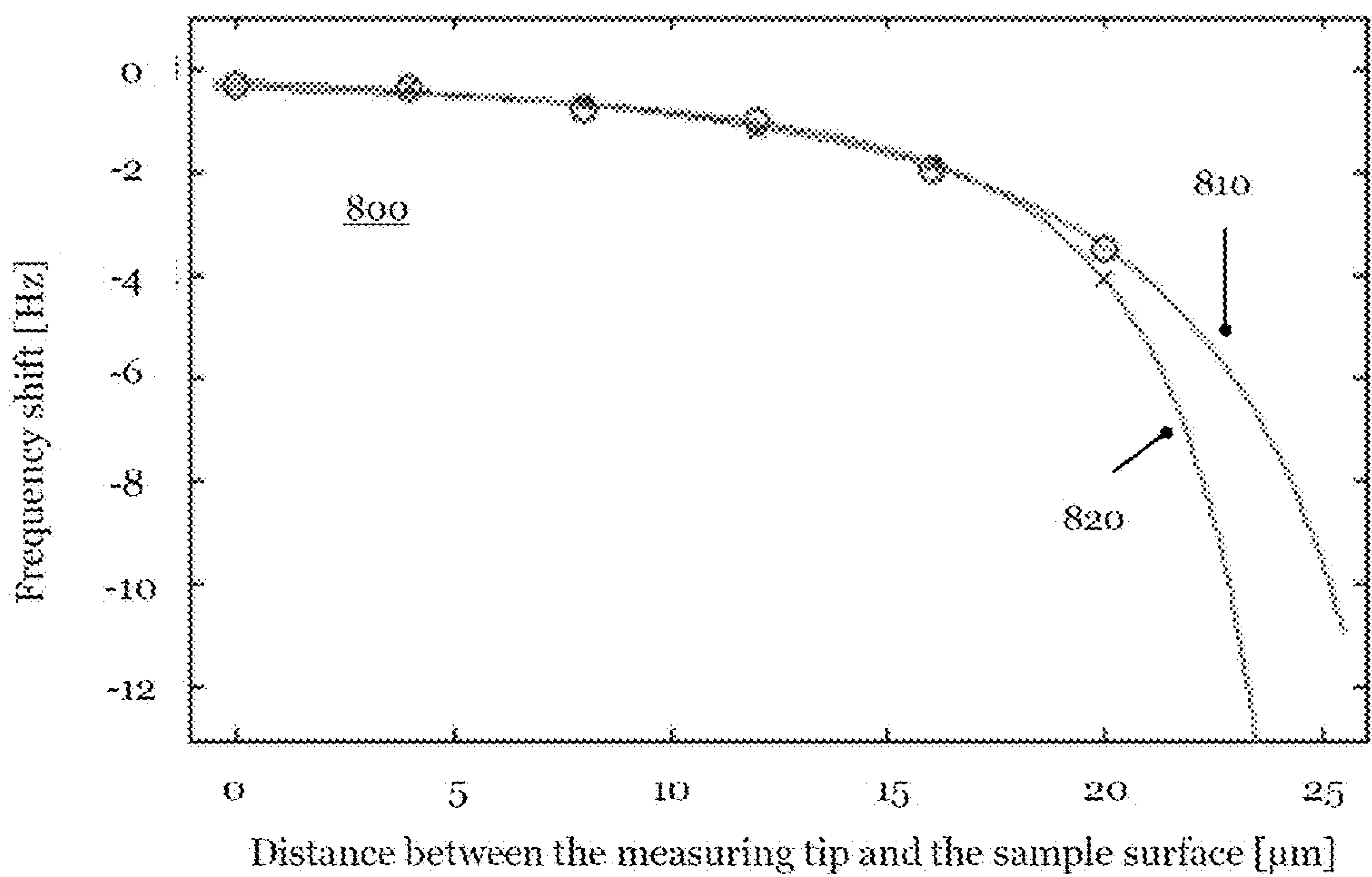


FIG. 6

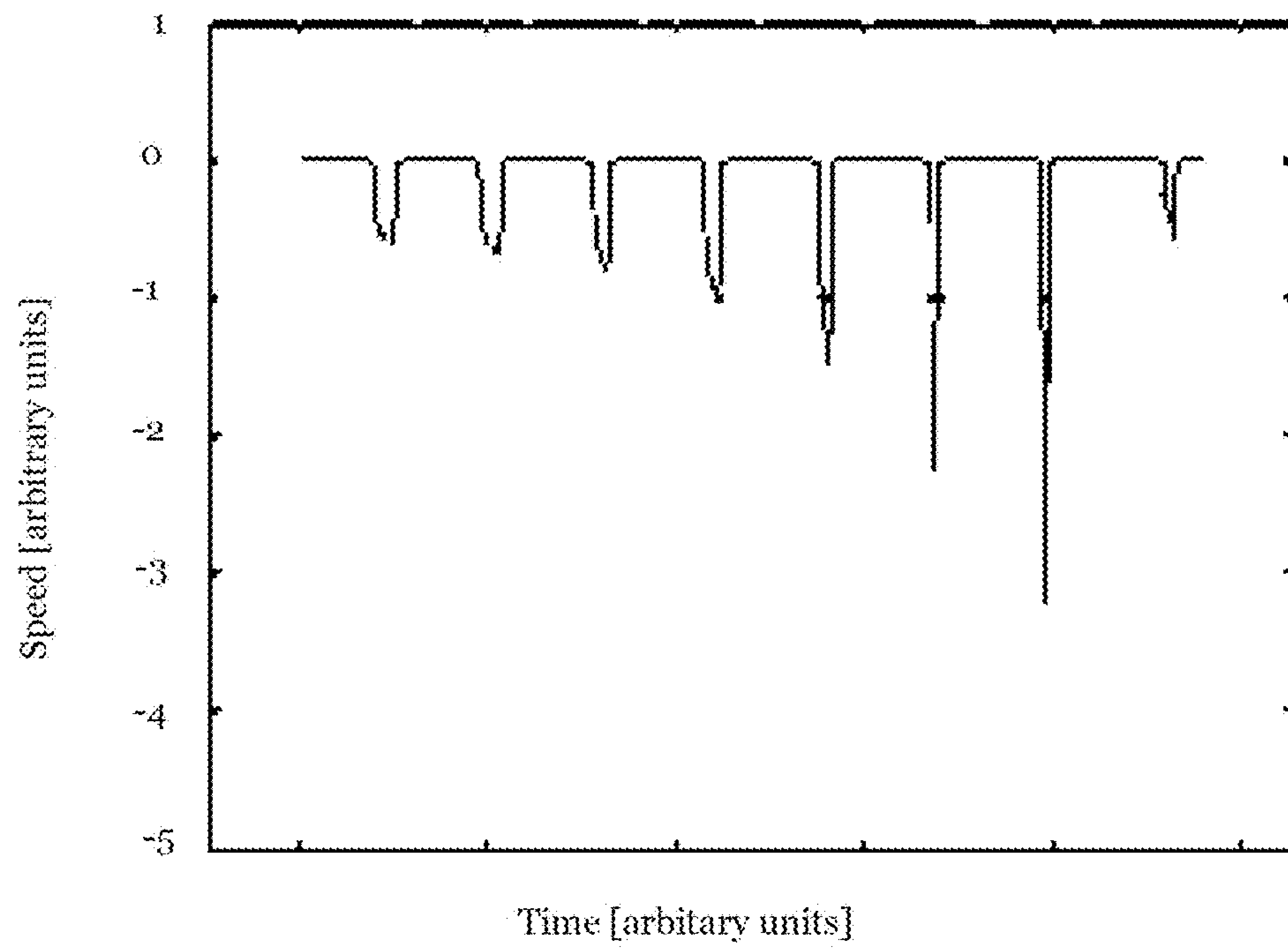


FIG. 7

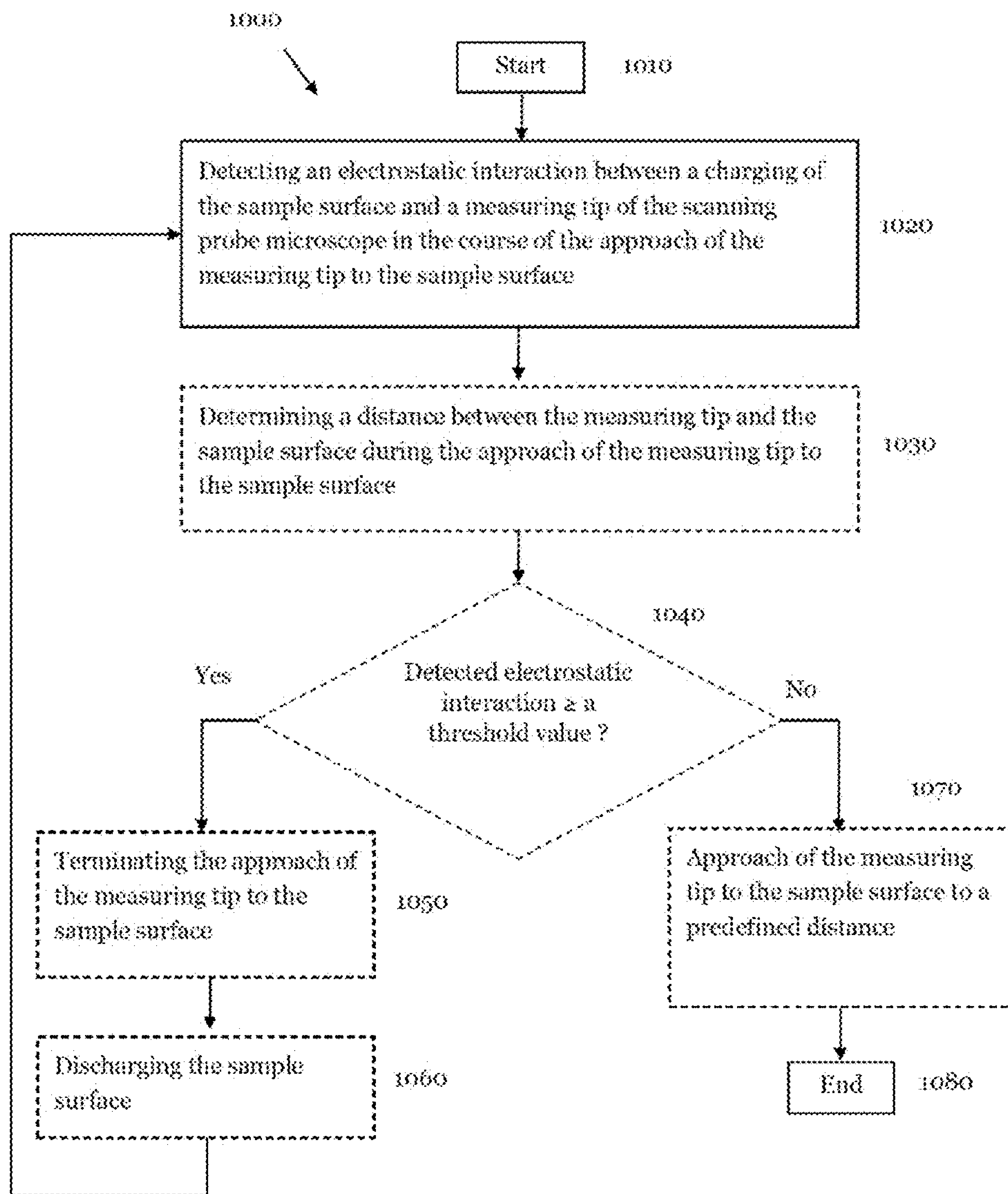


FIG. 8

METHOD AND APPARATUS FOR AVOIDING DAMAGE WHEN ANALYSING A SAMPLE SURFACE WITH A SCANNING PROBE MICROSCOPE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to German patent application 10 2016 204 034.0, filed on Mar. 11, 2016, the entire contents of which are herein incorporated by reference.

TECHNICAL FIELD

The present invention relates to a method and an apparatus for avoiding damage when analyzing a sample surface with a scanning probe microscope.

BACKGROUND

Advances in nanotechnology make it possible to produce components with increasingly smaller structure elements. Photolithographic masks are often used for producing microstructured components or circuits. On account of the ever decreasing dimensions of the structure elements, said masks cannot always be produced without defects that are visible or printable on a wafer. Owing to the costly production of photolithography masks, photomasks or simply masks, defective photomasks are repaired, whenever possible. Charged particle beams such as, for instance, ion beams or electron beams in combination with a suitable gas or a gas mixture are typically used for this purpose. By way of example, this is explained in the article "Increasing mask yield through repair enhancement utilizing the MeRit®" by A. Garetto, J. Oster, M. Waiblinger and K. Edinger, 26th European Mask and Lithography Conference, Proc. SPIE, Vol. 7545, 75450H1-754450H9 and in WO 2010/072 279 A1. Said charged particles may lead to an electrical charging of a mask surface.

Besides charged particles, high-energy photon beams, for example extreme ultraviolet (EUV) radiation, that are used for the exposure of reflective EUV masks may also have an ionizing effect and lead to an electrical charging of a mask surface as a result. Furthermore, process steps when producing photomasks, such as etching processes, for instance, may lead to a charging of the mask surface. Moreover, the handling of a sample, for example of a wafer or of a photomask, may already lead to an electrostatic charging of the surface thereof. If the specimen is a wafer to be processed, coating processes and/or etching processes may also result in an electrical charging of the sample.

In the case of samples that have an electrically conductive surface, electrical charging can be avoided by earthing the sample. In the case of electrically insulating or semiconducting samples, surface charges can be prevented by vapor-depositing a thin conductive layer onto the surface of a sample to be examined. This last step may not be possible, however, for many applications, particularly if the samples to be analyzed are used in the production of, for example, microstructured semiconductor components or the production and/or repair of photomasks.

An electrostatic charging of a photomask or generally of a sample surface may obstruct subsequent examinations. By way of example, it may be necessary to analyze the surface of a photomask or of a sample with a scanning probe microscope such as, for instance, an atomic force microscope (AFM) or scanning force microscope (SFM). However, this may encounter difficulties since an electrostatic charging of the sample surface may corrupt a direct examination with a scanning probe microscope on account of the electrostatic interaction between the sample surface and a conductive measuring tip of the scanning probe microscope. This means that an electrical charging of the sample may make it impossible to analyze the topography thereof. Worse still, an electrical charging of the sample surface, in the course of the approach of a conductive measuring tip to the sample surface, may discharge like a flash (tip discharge), wherein the electrical charge of the sample surface may flow away via the measuring tip of the scanning probe microscope. The sudden discharge of the sample surface may lead to damage to a conductive measuring tip and/or a sample surface.

FIG. **1** shows the image of an excerpt from a photomask having damage that arose in the course of the approach of a conductive measuring tip of a scanning probe microscope to the electrostatically charged surface of the photomask. The image in FIG. **1** was recorded by a scanning electron microscope. The damage brought about by the electrostatic charging of the photomask is referred to as ESD damage (for electro-static damage). The damage shown in FIG. **1** can't be repaired and may thus lead to a loss of the illustrated photomask, which has to be produced anew in a time-consuming and costly process.

Besides the damage to sample surfaces as illustrated in FIG. **1**, normally the measuring tips are altered by the high current density of the discharge current and have to be exchanged after an uncontrollable discharge of an electrostatically charged sample surface. (This is not shown in FIG. **1**). To summarize, FIG. **1** illustrates that a discharge of a sample surface such as a flash via a conductive measuring tip of a scanning probe microscope must be prevented.

By use of a targeted discharge of an electrostatically charged surface of a sample, for example of a photomask, it is possible at least partly to prevent ESD damage during the use of a scanning probe microscope. One possibility for discharging a sample surface is to fit electrical contacts to the sample. However, this is of no help in the case of a local electrostatic charging, such as occurs on photomasks, for example, which preferably have a multiplicity of insulated electrically conductive structure elements fitted on an electrically insulating quartz substrate. Another possibility for discharging a sample surface with the aid of a corona discharge is disclosed in DE 10 2013 212 957 A1.

The discharge of a sample surface by the method mentioned requires, on the one hand, the additional incorporation of a corona discharge unit in the vicinity of that region of a sample which is intended to be examined by a measuring tip of a scanning probe microscope, or on the other hand—if the discharge is effected with the aid of radioactive substances—handling with these substances. Furthermore, it is difficult to control the discharge of a sample surface, and so local chargings may still be present on a sample surface even after a discharge process.

The examination of electrically charged surfaces with a scanning probe microscope has already been intensively investigated. The authors M. Nonnenmacher, M. P. O'Boyle and H. K. Wickramasinghe, Appl. Phys. Lett. 58, 2921 (1991) and also J. M. R. Weaver and D. W. Abraham, J. Vac. Sci. Techn., B9, 1159 (1991) describe a Kelvin force microscope that can be used to minimize the contribution of the electrostatic force to the oscillation frequency of the measuring tip. U.S. Pat. No. 5,308,974 discloses a method in which a sample to be examined is scanned once in contact with the sample surface in order to record topographical

information and once using the topographical information recorded in the first scan, in order to separate the different force contributions acting on the measuring tip of a cantilever. In the article "High-resolution capacitance measurement and potentiometer by force microscopy", the authors Y. Martin, D. A. Abraham and H. K. Wickramasinghe, Appl. Phys. Lett. 52, 1103, 1988, theoretically and experimentally investigate the behavior of the electrostatic interaction between an earthed sample and an electrostatically charged measuring tip of a force microscope in a one- and two-digit distance range between sample and measuring tip.

However, the cited documents do not appear to address the subject of an uncontrolled discharge of a charged sample surface via an electrically conductive measuring tip and the attendant ESD damage of the sample surface and/or of the measuring tip of the scanning probe microscope.

Therefore, the present invention addresses the problem of specifying a method and an apparatus which avoid damage when analyzing a charged sample surface with a scanning probe microscope.

SUMMARY

In accordance with one exemplary embodiment of the present invention, this problem is solved by a method for avoiding damage when analyzing a sample surface with a scanning probe microscope, in which the method comprises the step of: detecting an electrostatic interaction between a charging of the sample surface and a measuring tip of the scanning probe microscope in the course of the approach of the measuring tip to the sample surface already at a distance from the sample surface which is greater than the distance of the measuring tip when analyzing the sample surface.

The potentials of a sample surface which lead to attractive or repulsive forces fall sharply with increasing distance from the sample surface; by way of example, the Lennard-Jones potential has an attractive portion, which falls with r^{-6} and is caused by the van der Waals interaction, and a repulsive portion, which varies proportionally to r^{-12} (cf.: F. J. Giessibl: "Advances in atomic force microscopy", Reviews of Modern Physics, May 2003). The potential distribution of an electrical charging has a potential profile that varies with r^{-1}. This means that an electrostatic charging of a sample surface has appreciable potential portions at large distances (>1 μm) from the sample surface at which the short-range potentials of the sample surface (<100 nm) are no longer detectable.

The inventors have discovered, by use of comprehensive analyses, that this circumstance can be utilized to detect a possibly present (local) electrostatic charging of the sample surface already in the course of the approach of a measuring tip to the sample surface in preparation for the actual measuring process of the scanning probe microscope. In other words, the measurement of an electrostatic charging is carried out at a distance between the measuring tip and the sample surface which is significantly greater than the distance of the measuring tip when examining the sample surface (for example >1 μm). It thus becomes possible, as early as during the approaching process and thus in a timely manner, to initiate suitable countermeasures which prevent an uncontrolled discharge of the sample surface via the measuring tip of the scanning probe microscope and the attendant typical damage discussed in the first part.

According to another aspect, the method furthermore comprises the step of: terminating the approach of the measuring tip to the sample surface as soon as the detected electrostatic interaction exceeds a threshold value.

On account of the slow fall in the potential of an electrostatic charging, an electrostatic charging of the sample surface can be determined quantitatively even when there is a large distance (>1 μm) between sample and measuring tip. As a result, when a charging of the sample surface that is greater than a predefined threshold value is present, the lowering of the measuring tip onto the surface of the sample or in the immediate vicinity thereof can be stopped before a spark can jump across between measuring tip and sample surface and can cause ESD damage to the sample surface and/or the measuring tip of the scanning probe microscope.

A threshold value may be an individual numerical value, for example a predefined electrostatic force that acts on the measuring tip at a specific distance between the measuring tip and the sample surface. However, a threshold value may also be determined by a setpoint curve or a defined deviation from a setpoint curve. Furthermore, a threshold value may be determined from a curve derived from a setpoint curve, for instance an envelope curve, or a variable derived from a setpoint curve, such as, for instance, a predefined frequency shift of the resonant frequency of a cantilever of the scanning probe microscope.

According to a further aspect, the method furthermore comprises the step of: determining a distance between the measuring tip and the sample surface during the approach of the measuring tip to the sample surface.

By virtue of the fact that in parallel with the lowering of the measuring tip onto the sample surface, proceeding from a macroscopic distance (>10 μm), the distance between the sample surface and the measuring tip is measured, the magnitude of the electrostatic charging at the point of impingement of the measuring tip on the sample can be determined even when there is a large distance between the measuring tip and the sample surface.

According to another aspect, the measuring tip comprises electrically conductive and/or semiconducting material. In accordance with yet another aspect, the electrically conductive material comprises a metal such as, for example, tungsten, cobalt, iridium or iron and/or a metal alloy such as, for example a gold alloy. According to yet another aspect, the semiconducting material comprises silicon, in particular heavily n-doped silicon.

An electrostatic charging of a sample surface induces in an electrically conductive measuring tip a charge or an image charge having a sign complementary to that of the charging of the sample surface. As a result, an attractive potential between the measuring tip and the sample surface arises independently of the sign of the electrostatic charging of the sample surface.

According to yet another aspect, the distance between the measuring tip and the sample surface at the beginning of the approach is in a range of 1000 μm to 10 μm, preferably 500 μm to 20 μm, more preferably 250 μm to 40 μm, and most preferably of 125 μm to 80 μm. In accordance with one preferred aspect, an approach speed between the sample surface and the measuring tip comprises a range of 0.01 μm/s to 100 μm/s, preferably 0.1 μm/s to 30 μm/s, more preferably 0.5 μm/s to 10 μm and most preferably 1.0 μm/s to 5.0 μm/s.

According to one advantageous aspect, the method furthermore comprises the step of: determining a deflection of a cantilever of the scanning probe microscope, to which the measuring tip is fixed, during the approach of the measuring tip to the sample surface.

As already explained above, an electrostatic charging of a sample leads to an attractive electrostatic force between the measuring tip of a scanning probe microscope and the

sample surface. This force results in a deflection, excursion or bending of a cantilever to whose free end the measuring tip is fitted. The cantilever or the excursion thereof acts as a force sensor for the charging of a sample surface. By measuring the extent of the bending of the cantilever and the distance between the measuring tip and the sample surface, the magnitude of the charging of a sample can be determined even when there is a large distance (>1 μm) between the measuring tip and the sample surface.

In accordance with one advantageous aspect, detecting the electrostatic interaction is effected by use of a force sensor.

By virtue of the force sensor being embodied as part of the cantilever, it is possible to construct a scanning microscope compactly. As a result, the range of application of said microscope can be increased.

In one advantageous aspect, the method comprises the step of: generating an oscillation of the measuring tip before the beginning of the approach of the measuring tip to the sample surface.

The above-described method for avoiding damage when analyzing a sample surface can be used for all operating modes of a scanning probe microscope, i.e. for example for a mode in which the measuring tip is guided in contact with the sample or at a fixed distance above the surface thereof. Furthermore, a scanning probe microscope may operate in an operating mode in which a cantilever carrying the measuring tip at its free end oscillates at or near the resonant frequency of the cantilever.

According to one preferred aspect, the method furthermore comprises the step of: determining a change of an amplitude, a phase and/or a frequency of the generated oscillation and/or a quality factor of the force sensor during the approach of the measuring tip to the sample surface.

The electrostatic interaction between the measuring tip and a charged sample changes the generated constrained oscillation of the system comprising the cantilever and the measuring tip. Various variables characterizing a constrained oscillation can be used for detecting the electrostatic interaction.

In accordance with yet another aspect, the oscillation of the measuring tip comprises a frequency range of 5 kHz to 5 MHz, preferably 10 kHz to 1 MHz, more preferably 20 kHz to 500 kHz, and most preferably 30 kHz to 200 kHz. According to a further aspect, an oscillation amplitude of the measuring tip has a range of 0.002 nm to 2000 nm, preferably of 1 nm to 1000 nm, and most preferably of 10 nm to 500 nm.

One preferred aspect furthermore comprises the step of: determining a lateral position of the measuring tip with respect to the sample surface with a positioning sensor and/or determining a distance between the measuring tip and the sample surface with a distance measuring system. In accordance with yet another aspect, the positioning sensor comprises an interferometer, in particular a laser interferometer and/or a white light interferometer. According to another aspect, the distance measuring system comprises an interferometer, in particular a laser interferometer and/or a white light interferometer. Furthermore, the distance measuring system may use capacitive sensors and/or distance sensors. Furthermore, it is possible to measure a lateral distance between the measuring tip and the sample surface once and then to determine the lateral position with the aid of a stepper motor.

Yet another advantageous aspect comprises the step of: determining the electrostatic interaction between the sample surface and the measuring tip from a detuning of the generated oscillation of the measuring tip.

Yet another aspect furthermore comprises the step of: generating the charging of the sample surface by use of a charged particle beam and/or by use of a photon beam. In accordance with yet another aspect, the charged particle beam comprises an electron beam and/or the photon beam comprises a photon beam for the extreme ultraviolet wavelength range.

In accordance with yet another aspect, the scanning probe microscope comprises an atomic force microscope or a scanning force microscope.

One advantage of a method according to the invention is that it can be introduced subsequently into existing scanning probe microscopes, without new components having to be added to the existing measuring systems of the scanning probe microscope. According to one particularly useful aspect, an apparatus for avoiding damage when analyzing a sample surface with a scanning probe microscope comprises means for detecting an electrostatic interaction between a charging of the sample surface and a measuring tip of the scanning probe microscope in the course of the approach of the measuring tip to the sample surface already at a distance which is greater than the distance of the measuring tip when analyzing the sample surface.

An apparatus according to the invention reliably prevents ESD (electro-static damage) damage when examining an electrostatically charged sample surface with the aid of a scanning probe microscope. An apparatus according to the invention thus protects both the sample surface to be examined and the measuring tip of the scanning probe microscope.

According to a further aspect, the means for detecting an electrostatic interaction between the charging of the sample surface and the measuring tip of the scanning probe microscope comprises a force sensor.

In accordance with one advantageous aspect, the apparatus furthermore comprises means for terminating the approach of the measuring tip to the sample surface as soon as the detected electrostatic interaction exceeds a threshold value.

According to one advantageous aspect, the apparatus furthermore comprises means for determining a distance between the measuring tip and the sample surface during the approach of the measuring tip to the sample surface.

The means for determining the distance between the measuring tip and the sample surface during the approach of the measuring tip to the sample surface can comprise a distance measuring system.

The means for terminating the approach of the measuring tip to the sample surface can comprise a control device configured to determine the distance between the measuring tip and the sample surface from a signal of the distance measuring system, and to stop an approach of the measuring tip to the sample surface by outputting a control signal to a positioning system and/or to a piezo-actuator.

The means for detecting the electrostatic interaction can comprise a computing unit configured to determine the electrostatic charging of the sample surface from a signal of the force sensor and the distance between the measuring tip and the sample surface, said distance being determined by the control device.

According to a further aspect, the apparatus comprises a modified scanning electron microscope. Finally, in accordance with yet another aspect, the modified scanning electron microscope comprises supply containers for at least one etching gas and least one deposition gas, at least one

metering valve for each supply container and/or at least one feedline system for providing the at least one etching gas and/or the at least one deposition gas at the location where an electron beam of the modified scanning electron microscope impinges on the sample surface.

According to one advantageous aspect, a computer program comprises instructions which, when they are executed by one of the apparatuses in the preceding aspects, cause the apparatus to perform the method steps in one of said aspects.

BRIEF DESCRIPTION OF DRAWINGS

The following detailed description describes currently preferred exemplary embodiments of the invention, with reference being made to the drawings, in which:

FIG. **1** represents ESD damage to a photomask that arose during discharges of an electrostatically charged photomask via a measuring tip of a scanning probe microscope;

FIG. **2** reproduces a schematic section through some important components of an atomic force microscope which comprises an apparatus according to the invention;

FIG. **3** illustrates a schematic section through a combination of a scanning electron microscope and an atomic force microscope;

FIG. **4** shows various forces emanating from a sample as a function of the distance from the surface thereof;

FIG. **5** represents a frequency shift of an FM-modulated AFM as a function of the distance between the measuring tip and a sample surface charged in a defined manner;

FIG. **6** shows a frequency shift in the course of approaching an electrostatically charged photomask;

FIG. **7** illustrates a change in speed of the measuring tip of an atomic force microscope in the course of the approach of the measuring tip to an electrostatically charged photomask; and

FIG. **8** shows a flow diagram of a method for avoiding damage when analyzing a sample surface with a scanning probe microscope.

DETAILED DESCRIPTION

Currently preferred embodiments of the method according to the invention for avoiding damage when analyzing a sample surface are explained in greater detail below on the basis of the example of an atomic force microscope (AFM) and a combination of a scanning electron microscope and an AFM. However, the method according to the invention is not restricted to the examples discussed below. Moreover, this method can be used for arbitrary scanning probe microscopes whose force sensor can detect an electrostatic interaction between a sample and a measuring tip of a scanning probe microscope. Furthermore, the application of the method according to the invention is not restricted to the samples mentioned below. Rather, this method can be used for avoiding damage when examining electrically conductive, electrically insulating and/or semiconducting samples.

The diagram **400** in FIG. **2** reproduces a schematic section through some important components of a scanning probe microscope **425** in the upper sub-illustration. In the example illustrated in FIG. **2**, the scanning probe microscope **425** is a scanning force microscope or an atomic force microscope (AFM). A sample **405** to be examined is fixed on a sample stage **415**. This can be done for example by suction exerted on the sample **405** with a reduced pressure by use of the sample stage **415** or by an electrostatic interaction between the sample stage **415** and an electrically conductive rear side of the sample **405**.

The sample **405** may be an arbitrary microstructured component or structural part. By way of example, the sample **405** may comprise a transmissive or a reflective photomask and/or a template for nanoimprint technology. Furthermore, the atomic force microscope **425** may be used for examining for example an integrated circuit, a microelectromechanical system (MEMS) and/or a photonic integrated circuit.

In the case of an electrostatically charged sample **405**, the electrical charge may be localized on the surface **410** of the sample **405**. However, a sample **405** is also electrostatically charged if electrical charge exists in a conductive layer above which a thin oxide layer is present, as is the case for example in the gate channel of a MOSFET. An electrical charge arranged a few micrometers below the sample surface **410** likewise leads to an electrostatic potential distribution in the space above the sample surface **410**.

As symbolized by the arrows in FIG. **2**, the sample stage **415** can be moved by a positioning system **420** in three spatial directions relative to the AFM **425**. In the example in FIG. **2**, the positioning system **420** is embodied in the form of a plurality of micromanipulators **420**. An alternative embodiment of the positioning system **420** might be piezo-actuators. The positioning system **420** or the micromanipulators **420** are controlled by signals of the control unit **480**. In an alternative embodiment, the positioning system **420** does not move the sample stage **415**, but rather the mount **450** to which the AFM **425** is fitted. It is furthermore possible for the positioning system **420** to perform a coarse positioning of the sample **405** in height (z-direction) and for a piezo-actuator **430** of the AFM **425** to perform a precise height setting of the AFM **425**.

In the example in FIG. **2**, the scanning probe microscope **425** or the AFM **425** comprises a piezo-actuator **430**, with the aid of which the probe **435** of the AFM **425** can be scanned over that part of the surface **410** of the sample **405** which is to be examined. The probe **435** comprises a movable lever arm **440**, which is referred to hereinafter as the cantilever **440**. Attached to the free end of the cantilever **440** is the measuring tip **445**. In the example shown in FIG. **2**, the AFM **425** comprises a cantilever **440** and a measuring tip **445** composed of highly doped silicon. Preferably, the cantilever **440** and the measuring tip **445** are n-doped. However, it is also possible for the cantilever **440** and the measuring tip **445** to be formed from a metal or a metal alloy, such as, for instance, to be produced from tungsten, cobalt, iridium or iron and/or from a metal alloy, such as a gold alloy, for example. It is furthermore conceivable to apply a thin metal layer to a semiconducting measuring tip, for instance a silicon measuring tip, or an insulating measuring tip, such as a silicon nitride measuring tip, for example. If losses in the sensitivity of the detection of an electrostatic charging can be accepted, an electrically insulating measuring tip can also be used.

The cantilever **440** can furthermore comprise a force sensor **442** in the form of a sensor element which measures the excursion of the cantilever **440**. The sensor element can be embodied for example in the form of a piezoresistive sensor. The signal of the sensor element **442** is forwarded to the control unit **480**. The control unit **480** can output a corresponding actuating signal to the piezo-actuator **430**. The piezo-actuator **430** of the AFM **425** can thus be operated in a closed control loop. Moreover, the control unit **480** can furthermore output a signal to the piezo-actuator **430**, such that the latter scans over the sample **405** in order to determine a two- or three-dimensional contour of the surface **410** of the sample **405**. In addition, the control unit **480** can

provide a signal to the piezo-actuator **430** in order to alter the distance between the measuring tip **445** and the sample surface **410**.

The lower sub-illustration in FIG. **2** shows a second embodiment of an AFM **425**. This embodiment comprises a piezo-actuator **430** and a probe. The probe comprises a plate **462**, for example a quartz plate, on which the probe is secured to the piezo-actuator **430**. A tuning fork, preferably in the form of a quartz tuning fork **460**, is fitted to the plate **462**. The free end of the tuning fork **460** carries a cantilever **440** with a measuring tip **445**. The corresponding statements with respect to the embodiment of the upper sub-illustration in FIG. **2** are applicable to the cantilever **440** and the measuring tip **445** in the embodiment of the lower sub-illustration.

By applying an electrical AC voltage, it is possible for the tuning fork **460** and thus the cantilever **440** together with the measuring tip **445** to be caused to oscillate. In order to optimize the sensitivity of the AFM **425**, it is advantageous to excite the tuning fork **460** at its resonant frequency, or at the resonant frequency of the oscillating system comprising tuning fork **460**, cantilever **440** and measuring tip **445**. As will be discussed in detail in the context of FIG. **5**, an electrostatic interaction of a conductive measuring tip **445** with a sample surface **405** leads to a detuning of the tuning fork **460**. The tuning fork **460**, the cantilever **440** and the measuring tip **445** function in the lower part as a force sensor **465** of the AFM **425**. The measurement signal of the force sensor **465** of the AFM **425** is provided to the control unit **480**.

The AFM **425**, as illustrated in the upper sub-illustration in FIG. **2**, is fixed to a mount **450** at the opposite end of the piezo-actuator **430** relative to the cantilever **440**. The mount **450** is normally earthed (not illustrated in FIG. **2**). Consequently, the measuring tip **445** of the AFM **425** is typically at earth potential. However, it is also possible to bring the measuring tip **445** of the AFM **425** to a defined potential. The electrostatic force between the surface **410** of the sample **405** and the measuring tip **445** can thereby be modified, in particular reduced.

A distance measuring system **455** can be fitted to the mount **450**. In the exemplary diagram **400** in FIG. **2**, the distance measuring system **455** comprises a laser interferometer that optically measures the distance between the sample surface **410** and the mount **450** and thus the distance between the sample surface **410** and the measuring tip **445** of the AFM **425**. The light beam **458** of the distance measuring system **455** can measure the distance between the sample surface **410** and the measuring tip **445** in real time, while the positioning system **420** alters the distance between the sample surface **410** and the measuring tip **445**. The distance measuring system **455** forwards the measurement data to the control unit **480**, which moreover can also control the operation of the distance measuring system **455**.

In an alternative embodiment, the approach of the measuring tip **445** to the sample surface **410** can be measured on an uncharged sample **405** and the data can be stored in a non-volatile memory of the control unit and/or of the computing unit **485**.

The diagram **400** furthermore represents a position sensor **470**, which optically **472** detects the lateral position of the sample **405** at which the measuring tip **445** of the AFM **425** interacts with the sample surface **410**. In an alternative embodiment, the position sensor **470** may comprise a camera, for example a CCD (Charge Coupled Device) camera and a light source appropriately matching the latter. It is furthermore possible to combine the distance measuring system **455** and the position sensor **470** in one apparatus (not illustrated in FIG. **2**).

The control unit **480** obtains the measurement data of the position sensor **470** and can thus position the region to be examined of the sample surface **410** below the measuring tip **445** of the AFM **425** by controlling the positioning system **420**. The speed at which the sample **405** is raised by the positioning system **420** or, equivalently thereto, the speed at which the measuring tip **445** is lowered onto the sample surface **410** can be set by the control unit **480**. At the same time as raising the sample stage **415**, the positioning system **420** can move the sample stage **415** in one or both lateral directions in order to bring that part of the sample **405** which is to be examined under the measuring tip **445** of the AFM **425**.

The distance between the sample **405** and the measuring tip **445** at the beginning of the alignment process is dependent on the topography of the sample surface **410**. On the one hand, it should be ensured that the measuring tip **445** cannot inadvertently interact with the sample **405** or the surface **410** thereof. On the other hand, the distance between measuring tip **445** and sample surface **410** should not be chosen to be larger than necessary, in order that the alignment process is not unnecessarily extended temporally. If the sample **405** to be analyzed is a photomask, it is advantageous to choose a distance between the sample **405** and the measuring tip **445** of approximately 100 μm for the initial state. The time duration for the approach of measuring tip **445** and sample surface may then be in the range of a few minutes.

The measuring tip **445** of the AFM **425** may be at rest during the lowering process. However, if the AFM **425** operates in an operating mode in which the measuring tip **445** is caused to effect a constrained oscillation, it is advantageous to switch on the oscillation of the measuring tip **445** and of the cantilever **440** at the beginning of the lowering or alignment process. The sensitivity for detecting an electrostatic charging of a sample surface **410** with an oscillating measuring tip **445** is greater in comparison with a measuring tip **445** at rest.

The control unit **480** forwards the measurement data of a force sensor **442**, **465** of the AFM **425**, of the distance measuring system **455** to the computing unit **485**. The computing unit **485** determines the extent of the electrical charging of the sample surface **410** from these data of the control unit **480** and/or from stored distance data and can display these data by use of the monitor **495**. Furthermore, the computing unit **485** may comprise a volatile and/or non-volatile memory (not illustrated in FIG. **2**). A threshold value for a permissible electrostatic potential distribution and distance data between the measuring tip **445** and the sample surface **410** from a reference measurement may be stored in the non-volatile memory. Furthermore, a setpoint curve describing the electrostatic interaction between a sample surface **410** that is not electrostatically charged and the measuring tip **445** of the AFM **425** as a function of the distance between measuring tip **445** and sample surface **410** may be stored in the non-volatile memory. From the setpoint curve it is possible to derive an envelope curve indicating an electrostatic charging whose magnitude has, however, proved to be non-critical for the process wherein the measuring tip **445** approaches the sample surface **410**. Moreover, a threshold value for terminating the approach process can be determined from the stored setpoint curve, for example as a predefined deviation from the setpoint curve.

It is furthermore conceivable to analyze predefined electrostatic potential distributions with the AFM **425** and to determine therefrom profiles of the electrostatic interaction between the measuring tip **425** as a function of the distance from the sample surface **410** and to store these curves in the non-volatile memory. The computing unit **485** can then determine corresponding threshold values from these curves as necessary.

A determined electrostatic potential which is less than the threshold value is deemed to be non-critical. By contrast, if the computing unit **485** determines an electrostatic potential which is greater than the predefined threshold value, the computing unit **485** outputs a signal to the control unit **480**. The control unit **480** then causes the positioning system **420** and/or the piezo-actuator **430** to stop a further approach of the sample surface **410** to the measuring tip **445**.

The control unit **480** and the computing unit **485** are the most important components of an apparatus **490** according to the invention.

In the course of the approach of the earthed measuring tip **445** to an electrostatically charged sample surface **410**, electrical flashovers between the charged sample surface **410** and the measuring tip **445** can occur. The distance of the measuring tip **445** of the AFM **425** in the non-contact operating mode may go into the single-digit nanometer range. The diameter of a fine measuring tip **445** may likewise lie in this range. Therefore, even small potential differences or voltages of a few volts between the measuring tip **445** and the sample surface **410** suffice to generate high peak electric field strengths that may lead to uncontrollable flashovers. By stopping an approach of the measuring tip **445** and the sample surface **410** at distances at which electrical flashovers cannot occur, it is possible to prevent damage to the sample surface **410** as a result of ESD or even destruction of the sample **405** and/or damage to the measuring tip **445** of the AFM **425**.

FIG. **3** schematically shows a few components of a microscope system **500**, comprising a scanning electron microscope (SEM) **520** and a scanning probe microscope (AFM) **425** arranged alongside one another in a vacuum chamber **502**. In an alternative embodiment, the scanning electron microscope may be embodied in the form of a focused ion beam (FIB). The scanning electron microscope **520** is composed of an electron gun **525** and a column **530**. The electron gun **525** generates an electron beam **535** and the column **530** focuses the electron beam **535** and directs it onto a sample **405** or the surface **410** thereof.

The sample **405** is arranged on the sample stage **415**. In a manner similar to that in FIG. **2**, the sample stage **415** can be moved in three spatial directions relative to the SEM **520** and the AFM **425** by the positioning system **420**. In an alternative exemplary embodiment, the sample stage **415** may be immobile and the SEM **520** and the AFM **425** are moved individually or jointly relative to the sample stage **415** by one or a plurality of positioning systems **420**. Furthermore, it is possible to divide the relative movement arbitrarily between the analysis devices **520** and **425** and the sample stage **415**. By way of example, the sample stage **415** may be movable in the plane perpendicular to the electron beam **535** and the SEM **520** and the AFM **425** may be displaceable in the beam direction. As discussed above in the context of FIG. **2**, the movement may be implementable by one or a plurality of micromanipulators of a positioning system **420** (not shown in FIG. **3**).

The AFM **425** is fixed (not illustrated in FIG. **3**) to the housing of the electron gun **530** via the suspension **545**. A mount **450** guides the measuring head or the probe **435** of the AFM **425** into the vicinity of the first measuring point **590** at which the electron beam **535** impinges on the sample **405**. Furthermore, the mount **450** may comprise one or a plurality of displacement elements (not illustrated in FIG. **3**) in order to adapt the position of the AFM **425** to the sample **405** to be examined.

As explained in the discussion of FIG. **2**, the upper end of the piezo-actuator **430** of the AFM **425** is connected to the mount **450**. The other end of the piezo-actuator **430** carries the probe **435** of the AFM **425**. The measuring tip **445** of the cantilever **440** interacts with the sample **405** at the second measuring point **595**. The distance measuring system **455** of the AFM **425** is not shown in FIG. **3**, for reasons of clarity. In the microscope system **500**, the SEM **520** may be used for positioning the measuring tip **445** of the AFM **425**.

A detector **570** converts the secondary electrons generated by the electron beam **535** at the first measuring point **590** and/or electrons backscattered from the sample **405** into an electrical measurement signal and forwards the latter to the computer system **585**.

Moreover, the microscope system **500** may comprise an ion source **580** that provides low-energy ions for the case where the sample **405** is electrically insulating or has an electrically insulating surface layer. The ions discharge or reduce an electrostatic charging of the surface **410** of the sample **405** by the electron beam **535** and can thereby enable an examination of the sample surface **410** by the AFM **425**.

The computer system **585** comprises a control unit **480** and a computing unit **485**. The control unit **480** forwards the measurement signals of the detector **570** to the computing unit **485**, which analyzes the measurement signals and generates an image therefrom, said image being displayed in the display **595**. As discussed in the context of FIG. **2**, the computing unit **485** likewise processes the measurement signals of the distance measuring system **455**, of the position sensor **470**, of the cantilever **440** and, if appropriate, of the sensor element **442** of the AFM **425** and likewise displays them on the screen **495** and/or **595**. The computer system **585** can control the electron gun **525** and the column **530** of the SEM **520**. Moreover, the computer system **585** can control the AFM **425**. By applying electrical signals to the terminals of the piezo-actuator **430**, the computer system **585** can scan the latter in the x-direction and/or in the y-direction over the surface **410** of the sample **405**.

The microscope system **500** may comprise one or a plurality of pump systems in order to generate and maintain a vacuum, in particular a high vacuum, in the vacuum chamber **502** (not illustrated in FIG. **3**). In the example in FIG. **3**, the microscope system **500** comprises one AFM **425**. However, it is also possible for two or more AFMs to be arranged in the microscope system **500**.

Furthermore, the microscope system **500** may comprise one or a plurality of gas containers together with corresponding valves and gas feed line systems (likewise not shown in FIG. **3**). As a result, under the action of the electron beam **535** and of a process gas, a chemical reaction can be induced locally, by use of which chemical reaction the sample **405** can be altered locally in a targeted manner by material removal or material deposition. Moreover, it may be advantageous to install an additional suction extraction apparatus (likewise not illustrated in FIG. **3**) in the vicinity of the first measuring point **590**, in order to extract by suction the waste materials of the chemical reaction induced by the electron beam **535** from the reaction zone, such that they cannot contaminate the vacuum chamber **502**.

The diagram **600** in FIG. **4** shows the profile of various forces that the sample **405** exerts on the measuring tip **445**

of an AFM **425** as a function of the distance from a sample surface **410**. Hereinafter, the sample surface **410** is designated as xy-plane and the z-direction perpendicular thereto measures the distance from the sample surface **410**.

The potential energy between the measuring tip **445** of the AFM **425** and the sample **405** $V_{ts}(z)$ causes a component of the force $F_{ts}(z)$ between the measuring tip **445** and the sample **405**

$$F_{ts}(z) = -\frac{\partial V_{ts}(z)}{\partial z}.$$

Furthermore, it is possible to derive a force gradient between the measuring tip **445** and the sample **405**:

$$k_{ts}(z) = -\frac{\partial F_{ts}(z)}{\partial z} = \frac{\partial^2 V_{ts}(z)}{\partial z^2}.$$

The apparatus **490** uses the force $F_{ts}(z)$ or a variable derived therefrom to determine an electrostatic charging of the sample **405** or the surface **410** thereof.

FIG. **4** reproduces the simulated profile of various forces. The curve **610** represents the profile of short-range repulsive or repelling forces as a function of the distance from the sample surface **410**, i.e. of forces which are detectable only within a distance <1 nm from the sample surface **410**. Examples of short-range forces are chemical forces or the repulsion of overlapping atomic orbitals of measuring tip **445** and sample surface **410**.

As already mentioned in the third part, the van der Waals interaction has an attractive effect and decreases with the sixth power of the distance from the sample surface **410**. The van der Waals forces are reckoned among the long-range forces and are of relevance at a distance of <100 nm from the sample surface **410**. The curve **620** represents the profile of the van der Waals forces as a function of the distance from the sample surface **410**.

A further long-range interaction between the sample **405** and the measuring tip **445** of the AFM **425** is the electrostatic interaction. As likewise already explained in the third part of the description, the electrical potential decreases with z^{-1}, wherein z measures the distance from the sample surface **410**. An electrically charged sample surface **410** induces a mirror charge in an electrically conductive or semiconducting measuring tip **445** of the AFM **425** the sign of said mirror charge being opposite to that of the electrical charge of the sample **405** or the surface **410** thereof. In the case of an insulating measuring tip, an electrical charging of the sample **405** leads to a polarization of the measuring tip. The force of the electrostatic interaction is thus attractive, independently of the sign of the electrical charging of the sample surface **410**. The electrical force between a charged surface **410** and the measuring tip **445** varies with z^{-2} according to the relationship indicated above. This is symbolized by the curve **630** in FIG. **4**. At distances of >1 μm between the measuring tip **445** and the sample surface **410**, the electrical or electrostatic force is dominant.

In the configuration as illustrated in FIG. **2**, the AFM **425** or the force sensor **442**, **465** of the AFM **425** cannot differentiate between the different near-surface forces caused by the sample **405**. Rather, the force sensor **442**, **465** of the AFM **425** detects a superimposition of all the forces occurring. On account of the different potential or force profiles **610**, **620** and **630**, however, it is possible, in the region D in FIG. **4**, to analyze the electrostatic force in a manner substantially uninfluenced by the other forces emanating from the sample **405**. The extent of the region D in the z-direction and the lower threshold d_1 thereof are dependent on the material composition of the sample **405**. Typical values for D are in the range of 50 μm to 100 μm. The distance d_1 between the lower threshold and the sample surface **410** encompasses a range of 50 μm to 20 μm. It defines the threshold starting from which an electrical flashover between the measuring tip **445** and the sample surface **410** can occur in the case of a charged sample **405**.

In a static operating mode, i.e. without constrained oscillation of the cantilever **440**, the electrostatic $F_{ts}(z)$ force is determined directly from a Δl deflection of the cantilever **440** by the force sensor **442**: $F_{ts}(z)=k\cdot\Delta l$, wherein k denotes the spring constant of the cantilever **440**. In a first embodiment, the deflection or excursion of the cantilever **440** can be measured optically using a laser beam directed onto the rear side of the cantilever **440** and a photodiode such as, for instance, a four-quadrant photodiode. In a second embodiment, the deflection can be determined with the aid of the force sensor **442** or the sensor element **442**.

In a dynamic operating mode of the AFM **425**, the cantilever **440** of the AFM **425** is caused to effect a constrained oscillation by the tuning fork **460**, for example. In order to optimize the detection sensitivity, it is advantageous to excite the tuning fork **460** at its resonant frequency. (With the use of an AM-AFM, it is preferred to choose an excitation frequency near the resonant frequency.) The forces $F_{ts}(z)$ between the measuring tip **445** and the sample surface **410** vary the resonant frequency of the oscillating system. The amplitude, the frequency and the phase of the oscillation are altered in this case. As a result, the power loss and the quality factor of the oscillating system are likewise varied. The oscillating system comprises the tuning fork **460**, the cantilever **440** and the measuring tip **445**.

There are two important dynamic operating modes of an AFM **425**: Amplitude modulation operation (AM-AFM) and frequency modulation operation (FM-AFM). The method according to the invention can be used for both dynamic operating modes. Since the reaction time in the AM-AFM mode is long in comparison with a period of the oscillation, the FM-AFM operating mode is considered in more specific detail below.

In an FM-AFM operating mode, the force sensor **465** of the AFM **425** acts as an oscillator in a feedback loop. The resonant frequency of the force sensor **465** changes as a result of the forces $F_{ts}(z)$ between the measuring tip **445** and the sample surface **410**. A change in the resonant frequency or a shift in the oscillation frequency of the force sensor **465** is detected with the aid of an FM demodulator. A feedback loop is used in order to keep the force sensor **465** at its resonant frequency and to keep the oscillation amplitude of the force sensor **465** constant. For small oscillation amplitudes of the force sensor **465**, that is to say that the oscillation amplitude of the force sensor **465** is small by comparison with a change in the interaction force $F_{ts}(z)$ across an oscillation amplitude, the frequency shift of an FM-AFM is given by (cf. F. J. Giessibl: "Advances in atomic force microscopy", Reviews of Modern Physics, May 2003):

$$\Delta f = \frac{k_{ts}}{2k} f_0 = -\frac{f_0}{2k} \cdot \frac{\partial F_{ts}}{\partial z},$$

where k_{ts}, as defined above, is the force gradient between the measuring tip **445** and the sample surface **410**. The constant k denotes the spring constant of the force sensor **465** of the AFM **425** and f_0 is the resonant frequency of the force sensor **465** of the AFM **425** without interaction with the sample surface **410**. The frequency shift Δf is proportional to the force gradient between measuring tip **445** and sample surface **410**. An attractive interaction shifts the resonant frequency f_0 to lower frequencies.

As illustrated in the diagram **600** in FIG. **4**, the force or the sum of the forces acting on the measuring tip **445** of the AFM **425** proceeding from the sample surface **410** is a function of the distance between the measuring tip **445** and the surface **410** of the sample **405**. In the case of a large distance (z>10 μm) between measuring tip **445** and sample surface **410**, the force $F_{ts}(z)$ and thus the force gradient $k_{ts}(z)$ within a oscillation amplitude of the cantilever **440** or of the force sensor **465** can be considered to be independent of the distance between measuring tip **445** and sample surface **410**, as occurred in the above equation for the frequency shift Δf. The oscillation amplitude of the force sensor **465** is preferably in the range of 100 nm to 500 nm.

For the case where the measuring tip **445** is lowered onto the sample surface proceeding from a large distance, for example 100 μm, the force F_{ts} and the force gradient k_{ts} change. This leads to a change in the measured frequency shift Δf.

The diagram **700** in FIG. **5** shows the frequency shift Δf(z) as a function of the distance z between the measuring tip **445** and the sample surface **410** for a test structure that was charged to a voltage of 100 V. The long-range electrostatic interaction causes a frequency shift Δf (z), that depends very greatly on the distance z between the measuring tip **445** and the sample surface **410**. The test structures were produced in three different sizes: 0.064 mm^2, 0.25 mm^2 and with an area of >1 mm^2. It can be gathered from the diagram **700** that the magnitude of the frequency shift Δf(z) is not dependent on the area of the electrostatic charging. The solid line represents a simulation of the frequency shift with an approach

$$\propto = \frac{1}{z^2}$$

corresponding to the variation of the electrostatic force

$$F_{ts}(z) \propto \frac{1}{z^2}.$$

A significant frequency shift caused by a charged surface **410** can be reliably detected by an FM-AFM already for distances between measuring tip **445** and sample surface **410** that are greater than 10 μm. An FM-AFM in combination with a measurement of the distance between the measuring tip **445** and the sample surface **410** and/or with stored data can thus be used reliably for detecting an electrostatically charged surface **410**, without running the risk of the sample **405** and/or the measuring tip **445** being damaged by ESD damage.

The diagram **800** in FIG. **6** reproduces the frequency shift or frequency decrease Δf(z) for a photomask whose surface **410** is electrostatically charged. In the example illustrated in FIG. **6**, the lowering of the measuring tip **445** onto the surface **410** of the photomask begins at a distance of 25 μm between the surface **410** of the photomask and the measuring tip. This corresponds to the zero point of the abscissa.

The substrate of a photomask typically has unevennesses of <1 μm. Absorber structures on the substrate of a photomask have height dimensions of likewise significantly less than one micrometer. Therefore, in the example in FIG. **6**, the positioning system **420** can safely bring the measuring tip **445** and the surface **410** of a photomask closer to one another to a distance of 25 μm, without the risk of the measuring tip **445** and/or the mask surface being damaged. The detection of an electrostatic charging of the photomask is likewise not necessary up to the distance of 25 μm in the example in FIG. **6**.

The approach between the measuring tip **445** and the surface **410** of the photomask from a distance of 25 μm until the measuring tip **445** is placed onto the surface **410** of the photomask is effected with the aid of the piezo-actuator **430** of the AFM **425**. After each reduction of the distance between the measuring tip **445** and the sample surface of 4 μm, a measurement of the interaction between the measuring tip **445** and the sample **405** is carried out. The curve **810** represents the frequency shift—calculated from the measurement data—of an approach process in which the measuring tip **445** was retracted during the lowering process, i.e. the measuring tip **445** was at a maximum distance from the sample surface **410**. The curve **820** shows the approach process with an extended measuring tip **445**, i.e. the measuring tip **445** was inclined maximally with respect to the sample surface **410**. The distance of the measuring tip **445** in the z-direction between the two operating modes is in the region of 6 μm. The deviation of the curve **820** from the curve **810** in the case of a distance of 5 μm from the surface **410** of the photomask shows the presence of an electrostatic charging of the surface **410** of the photomask.

In the example illustrated in FIG. **6**, the sample stage **415** has a high-precision positioning system **420** having a repeat accuracy of <1 μm. After recording and storing a reference measurement in a non-volatile memory of the control unit **480** and/or the computing unit **490** for a photomask, it is possible to perform subsequent lowering processes of the measuring tip **445** onto the surface **410** of the photomask without a measurement of the distance between the measuring tip **445** and the surface **410** of the photomask with the aid of an accurate stepper motor.

FIG. **7** shows the step-by-step approach of the measuring tip **445** with the aid of the piezo-actuator **430**. Time is plotted on the abscissa, and the ordinate represents the speed or the approach speed of the measuring tip **445** in the direction of the sample surface **410**. In the time segments in which the measuring tip is not moved, i.e. $v_{MS}=0$ the sample stage **415** is raised by a predefined amount. In these time intervals, the measuring tip **445** is maximally retracted, i.e. it is at a maximum distance from the sample surface **410**. At the seven points in time indicated in FIG. **7**, the measuring tip **445** is extended from the maximally retracted position and then brought to the initial position again. The approach speed of the measuring tip **445** in the course of approaching the sample surface **410** is proportional to the frequency shift—caused by an electrical charging—of the oscillating measuring tip **445** ($v \propto \Delta f$). FIG. **7** clearly shows the frequency shift caused by an electrostatic interaction between measuring tip **445** and sample surface **410** in the form of the speed of change of the measuring tip **445**, said speed of change being increased as the z-distance of the measuring tip **445** decreases, in the course of approaching the sample surface **410**.

The flow diagram **1000** in FIG. **8** represents steps of the method for analyzing a sample surface **410** with a force sensor **442**, **465** of a scanning probe microscope **425**. The method starts at step **1010**. Step **1020** involves detecting an electrostatic interaction between a charging of the sample surface and a measuring tip **445** of the scanning probe microscope **425** in the course of the approach of the measuring tip **445** to the sample surface **410**.

The further method steps illustrated in the flow diagram **1000** are optional and therefore reproduced with a dashed frame. Step **1030** involves determining a distance between the measuring tip **445** and the sample surface **410** during the approach of the measuring tip **445** to the sample surface **410**. Decision block **1040** involves ascertaining whether the detected electrostatic interaction is greater than a predefined threshold value. In this case, the magnitude of the electrostatic charging on the sample surface **410** is deduced on the basis of the electrostatic interaction detected in step **1020** and the distance between the measuring tip **445** and the sample surface **410**, said distance being determined in step **1030**, at the point in time of detecting the electrostatic interaction.

If the detected electrostatic interaction is less than the predefined threshold value, in step **1070** the process of the approach of the measuring tip **445** to the sample surface **410** is continued until the measuring tip **445** has reached a predefined distance from the sample surface. During step **1070**, i.e. during the further approach, the magnitude of the electrostatic interaction is detected continuously or at intervals. If this exceeds a predefined threshold value, the approach process is terminated (not illustrated in the diagram **1000**). The method ends at step **1080**.

If the detected electrostatic interaction is greater than or equal to the predefined threshold, the approach of the measuring tip **445** to the sample surface **410** is terminated in step **1050**. The next step **1060** involves discharging the sample surface **410**. This can be carried out for example with the aid of the ion source **580**, the electron beam **535**, a corona discharge and/or a radioactive substance, such as polonium, for instance. The method then advances to step **1020** and detects once again the electrostatic interaction in relation to a charging of the sample surface **410** that is possibly still present.

In some implementations, instructions for carrying out one or more of the steps of the flow diagram **1000** can be stored in a computer-readable medium. The various calculations and the processing of signals in one or more of the steps of the flow diagram **1000** can be performed by, e.g., the computing unit **485**.

In some implementations, the computing unit **485** (and in some examples the control unit **480**) can include one or more processors and one or more computer-readable media (e.g., RAM, ROM, SDRAM, hard disk, optical disk, and flash memory). The one or more processors can perform various calculations and processing of the signals described above. The calculations and processing of signals can also be implemented using application-specific integrated circuits (ASICs). The term "computer-readable medium" refers to a medium that participates in providing instructions to a processor for execution, including without limitation, non-volatile media (e.g., optical or magnetic disks), and volatile media (e.g., memory) and transmission media. Transmission media includes, without limitation, coaxial cables, copper wire, fiber optics and free space. The memory can include any type of memory, such as RAM, ROM, SDRAM, and flash memory.

The features described above can be implemented advantageously in one or more computer programs that are executable on a programmable system including at least one programmable processor coupled to receive data and instructions from, and to transmit data and instructions to, a data storage system, at least one input device, and at least one output device. A computer program is a set of instructions that can be used, directly or indirectly, in a computer to perform a certain activity or bring about a certain result. A computer program can be written in any form of programming language (e.g., C, Java), including compiled or interpreted languages, and it can be deployed in any form, including as a stand-alone program or as a module, component, subroutine, a browser-based web application, or other unit suitable for use in a computing environment.

Suitable processors for the execution of a program of instructions include, e.g., general purpose microprocessors, special purpose microprocessors, digital signal processors, single-core or multi-core processors, of any kind of computer. Generally, a processor will receive instructions and data from a read-only memory or a random access memory or both. The essential elements of a computer are a processor for executing instructions and one or more memories for storing instructions and data. Generally, a computer will also include, or be operatively coupled to communicate with, one or more mass storage devices for storing data files; such devices include magnetic disks, such as internal hard disks and removable disks; magneto-optical disks; and optical disks. Storage devices suitable for tangibly embodying computer program instructions and data include all forms of non-volatile memory, including by way of example semiconductor memory devices, such as EPROM, EEPROM, and flash memory devices; magnetic disks such as internal hard disks and removable disks; magneto-optical disks; and CD-ROM, DVD-ROM, and Blu-ray BD-ROM disks. The processor and the memory can be supplemented by, or incorporated in, ASICs (application-specific integrated circuits).

While this specification contains many specific implementation details, these should not be construed as limitations on the scope of any inventions or of what may be claimed, but rather as descriptions of features specific to particular embodiments of particular inventions. Certain features that are described in this specification in the context of separate embodiments can also be implemented in combination in a single embodiment. Conversely, various features that are described in the context of a single embodiment can also be implemented in multiple embodiments separately or in any suitable subcombination.

Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the embodiments described above should not be understood as requiring such separation in all embodiments.

Thus, particular embodiments of the subject matter have been described. Other embodiments are within the scope of the following claims. In some cases, the actions recited in the claims can be performed in a different order and still achieve desirable results.

What is claimed is:

1. A method for avoiding damage when analyzing a sample surface with a scanning probe microscope, wherein the method comprises the following step:

detecting an electrostatic interaction between a charging of the sample surface and a measuring tip of the scanning probe microscope in the course of the approach of the measuring tip to the sample surface already at a distance from the sample surface which is greater than the distance of the measuring tip when analyzing the sample surface; and

terminating the approach of the measuring tip to the sample surface as soon as the detected electrostatic interaction exceeds a threshold value that depends on a distance between the measuring tip and the sample surface.

2. The method according to claim **1**, furthermore comprising the step of: determining the distance between the measuring tip and the sample surface during the approach of the measuring tip to the sample surface.

3. The method according to claim **1**, wherein the measuring tip comprises electrically conductive and/or semiconducting material.

4. The method according to claim **1**, wherein the distance between the measuring tip and the sample surface at the beginning of the approach is in a range of 1000 μm to 10 μm.

5. The method according to claim **1**, wherein an approach speed between the sample surface and the measuring tip comprises a range of 0.01 μm/s to 100 μm/s.

6. The method according to claim **1**, furthermore comprising the step of: determining a deflection of a cantilever of the scanning probe microscope, to which the measuring tip is fixed, during the approach of the measuring tip to the sample surface.

7. The method according to claim **1**, wherein detecting the electrostatic interaction is carried out by means of a force sensor.

8. The method according to claim **1**, furthermore comprising the step of: generating an oscillation of the measuring tip before the beginning of the approach of the measuring tip to the sample surface.

9. The method according to claim **8**, furthermore comprising the step of: determining a change of an amplitude, a phase and/or a frequency of the generated oscillation and/or a quality factor of the force sensor during the approach of the measuring tip to the sample surface.

10. The method according to claim **8**, furthermore comprising the step of: determining the electrostatic interaction between the sample surface and the measuring tip from a detuning of the frequency of the generated oscillation of the measuring tip.

11. The method according to claim **1**, wherein the scanning probe microscope comprises an atomic force microscope.

12. An apparatus for avoiding damage when analyzing a sample surface with a scanning probe microscope, wherein the apparatus comprises:

means for detecting an electrostatic interaction between a charging of the sample surface and a measuring tip of the scanning probe microscope in the course of the approach of the measuring tip to the sample surface already at a distance from the sample surface which is greater than the distance of the measuring tip when analyzing the sample surface; and

means for terminating the approach of the measuring tip to the sample surface as soon as the detected electrostatic interaction exceeds a threshold value that depends on a distance between the measuring tip and the sample surface.

13. The apparatus according to claim **12**, wherein the means for detecting the electrostatic interaction between the charging of the sample surface and the measuring tip of the scanning probe microscope comprises a force sensor.

14. The apparatus according to claim **12**, furthermore comprising: means for determining the distance between the measuring tip and the sample surface during the approach of the measuring tip to the sample surface.

15. The apparatus according to claim **14**, wherein the means for determining the distance between the measuring tip and the sample surface during the approach of the measuring tip to the sample surface comprises a distance measuring system.

16. The apparatus according to claim **12**, wherein the means for terminating the approach of the measuring tip to the sample surface comprises a control device configured to determine the distance between the measuring tip and the sample surface from a signal of the distance measuring system, and furthermore configured to stop an approach of the measuring tip to the sample surface by outputting a control signal to a positioning system and/or to a piezo-actuator.

17. The apparatus according to claim **16**, wherein the means for detecting the electrostatic interaction furthermore comprises a computing unit configured to determine the electrostatic charging of the sample surface from a signal of the force sensor and the distance between the measuring tip and the sample surface, said distance being determined by the control device.

18. A computer-readable medium storing a computer program comprising instructions which, when they are executed by the apparatus in claim **12**, causes the apparatus to perform a process comprising:

detecting the electrostatic interaction between the charging of the sample surface and the measuring tip of the scanning probe microscope in the course of the approach of the measuring tip to the sample surface already at a distance from the sample surface which is greater than the distance of the measuring tip when analyzing the sample surface; and

terminating the approach of the measuring tip to the sample surface as soon as the detected electrostatic interaction exceeds the threshold value, in which the threshold value depends on the distance between the measuring tip and the sample surface.

19. The method of claim **1**, comprising determining a setpoint curve describing an electrostatic interaction between a sample surface that is not electrostatically charged and the measuring tip as a function of a distance between the measuring tip and the sample surface.

20. The method of claim **19**, comprising, based on the setpoint curve, determining an envelope curve indicating an electrostatic charging whose magnitude is permissible.

21. The method of claim **19**, comprising determining the threshold value for terminating the approach of the measuring tip to the sample surface based on the setpoint curve.

22. The apparatus of claim **12**, comprising means for determining a setpoint curve describing an electrostatic interaction between a sample surface that is not electrostatically charged and the measuring tip as a function of a distance between the measuring tip and the sample surface.

23. The apparatus of claim **22**, comprising means for, based on the setpoint curve, determining an envelope curve indicating an electrostatic charging whose magnitude is permissible.

24. The apparatus of claim **22**, comprising means for determining the threshold value for terminating the approach of the measuring tip to the sample surface based on the setpoint curve.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 9,995,764 B2
APPLICATION NO. : 15/455305
DATED : June 12, 2018
INVENTOR(S) : Hans Hermann Pieper, Christof Baur and Rainer Fettig

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

On the Title Page

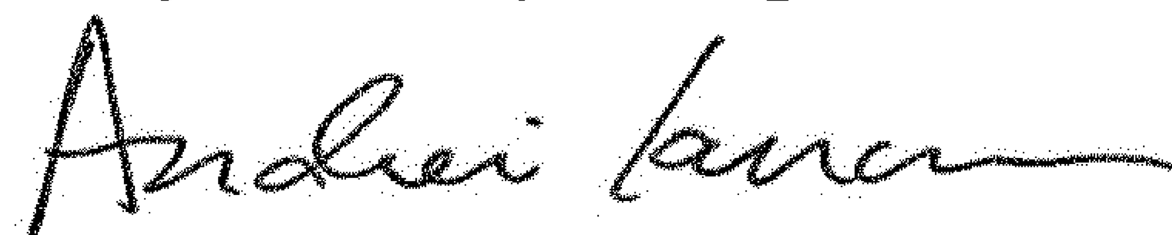
Column 1 item (Notice), Line 3, delete “0 days. days.” and insert -- 0 days. --

In the Specification

Column 14
Line 8, delete “50 μm” and insert -- 5 μm --

Column 16
Line 51, after “0” insert -- , --

Signed and Sealed this
Twenty-fifth Day of September, 2018



Andrei Iancu
Director of the United States Patent and Trademark Office